

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of

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Corres. to PCT/EP2004/013830

For: HEAT EXCHANGER, IN PARTICULAR FOR AN OVER CRITICAL COOLING
CIRCUIT

TRANSLATOR'S DECLARATION

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July 4, 2006

Date



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5 **Heat exchanger, in particular for supercritical
 refrigeration cycle**

The invention relates to a heat exchanger, in particular for a supercritical refrigeration cycle as described in the preamble of patent claim 1.

Heat exchangers for supercritical refrigeration cycles require a pressure-resistant design of tubes and headers, since the refrigeration process takes place at high pressures, up to about 120 bar. Heat exchangers of this type have been disclosed by DE-A 199 06 289, DE-A 100 07 159 and WO 98/51983 A. These known heat exchangers are in some cases used as gas coolers in a supercritical refrigeration cycle operated with CO₂ (R744); they are substantially characterized by a single-row design with two header tubes, i.e. one row of flat tubes which are formed as extruded multichamber tubes and have their ends secured in the header tubes and sealed, for example by brazing. The refrigerant flows through the gas cooler - as shown in DE-A 100 07 159 - in serpentine form, i.e. in multiple flows, with the refrigerant being diverted in a plane perpendicular to the direction of flow of the air, i.e. over the height or width of the gas cooler.

EP-B 414 433 has disclosed a refrigerant condenser in which two single-row heat exchangers are arranged in series in the direction of air flow and are connected in series on the refrigerant side (known as duplex heat exchangers). In the known condenser, refrigerant and air are routed in cross-countercurrent to one another, i.e. the refrigerant enters the leeward heat exchanger (row of tubes) and leaves the condenser via the

windward heat exchanger (row of tubes). Each row of tubes of a heat exchanger is divided into tube groups or tube segments, resulting in a decreasing cross section of flow for the condensing refrigerant. The rows of tubes comprise extruded flat tubes, between which corrugated fins are arranged. Each row of tubes, together with header tubes, forms a heat exchanger unit which is connected to the other heat exchanger unit by pieces of tube on the refrigerant side.

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A similar multi-row heat exchanger, a liquefier for a refrigerant of a vehicle air-conditioning system, has been disclosed by EP-B 401 752. In this case too, refrigerant, i.e. a conventional refrigerant, such as R 134a, is routed in cross-countercurrent with ambient air; in general four rows of tubes are arranged in series on the air side. These are round tubes with flat fins, i.e. a mechanically joined heat exchanger block.

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20 In motor vehicle air-conditioning systems, the condenser is arranged in the engine compartment of the motor vehicle upstream of the coolant/air cooler. The warmed air emerging from the condenser then flows through the coolant/air cooler. An arrangement of this type is also provided for gas coolers for CO₂ air-conditioning systems of the type described in the introduction - i.e. the single-row design with a relatively large end face which is matched to the coolant/air cooler located downstream of it. This design and arrangement has various drawbacks: firstly, arranging a gas cooler upstream of the coolant cooler impedes the power of the coolant cooler, on the one hand on account of the additional pressure-side pressure drop caused by the gas cooler and on the other hand on account of the warming of air caused by the dissipation of heat from the gas cooler to the air flowing through. Secondly, the gas cooler arranged upstream of the coolant cooler, at certain driving

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operating points, only receives certain air quantities as a function of the driving speed or the fan power. The air-conditioning of the motor vehicle is therefore very much dependent on the driving state of the vehicle. Consequently, one problem on which the invention is based consists in providing a heat exchanger, in particular for a supercritical refrigeration cycle, which avoids the abovementioned drawbacks.

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The article "Design Strategies for R744 Gas Coolers" von J.M. Yin, C.W. Bullard and P.S. Hrnjak (published in IIF-IIR Commission B1, B2, Purdue University USA-2000) compares and contrasts two configurations of gas coolers, namely what is known as the multi-pass heat exchanger, i.e. a single-row heat exchanger with medium flowing through it in multiple flows, and the multi-row countercurrent heat exchanger, in which three rows of tubes are provided connected in series on the refrigerant side. Since the refrigerant CO₂ (R744) enters the gas cooler in the supercritical state, i.e. in a single phase, it has a relatively high temperature gradient, unlike conventional refrigerant (R134a), which condenses at a constant temperature. This temperature gradient can be effectively reduced in a three-row countercurrent heat exchanger, for which reason the authors prefer this solution. Similar conclusions are reached by the authors J. Peterson, A. Hafner, and G. Skaugen in their article "Development of compact heat exchangers for CO₂ air-conditioning systems" (published in Int. J. Refrig. vol. 21, no. 3 pages 180-193, 1998). In this case too, the countercurrent heat exchanger (counterflow heat exchanger) with a reduced size of end face and increased depth in the direction of air flow is described as an advantageous gas cooler.

It is an object of the present invention to design a heat exchanger of the type described in the introduction which takes into account the conditions of a supercritical refrigeration cycle in terms of pressure and temperature gradient and has the highest possible efficiency (COP, i.e. coefficient of performance). Furthermore, the dimensions of this heat exchanger should be such that it can easily be accommodated in the engine compartment of a motor vehicle and can be supplied with sufficient cooling air.

This object is achieved by the features of patent claim 1. According to the invention, it is provided that the heat exchanger, which is preferably operated in countercurrent, has at least four rows of tubes, which are arranged in series in the direction of air flow. In this context, the term countercurrent is to be understood as meaning that the flow medium, preferably CO₂, first of all enters the leeward row of tubes and emerges again from the windward row of tubes. The cooling air which enters the heat exchanger meets a flow medium which has already been (pre)cooled in at least three rows of tubes. In these four rows of tubes, through which the medium flows in succession, the temperature gradient with a temperature difference of approx. 100 degrees Celsius can be effectively eliminated with a sufficiently low pressure drop on the air side. Forming the heat exchanger in at least four rows allows the surface area of the end face to be reduced, so that the heat exchanger acquires compact dimensions verging on a cube, which has the advantage that the heat exchanger, in particular if it is used as a gas cooler of a CO₂ air-conditioning system in the motor vehicle, can be accommodated at any desired point in the engine compartment of the vehicle. There is no need for it to be arranged upstream of the coolant cooler, which has the abovementioned drawbacks. The

heat exchanger can be cooled by additional air passages and a special fan. This also makes it independent of the driving states of the motor vehicle, with the result that constant air-conditioning of the vehicle interior is ensured. Furthermore, it has been found that the efficiency (COP) of the heat exchanger according to the invention is scarcely any worse than a comparable prior art heat exchanger.

10 According to an advantageous configuration of the invention, at least five or optimally six rows of tubes are arranged in series, resulting in the advantage of a further boost to the power of the heat exchanger, without the air-side pressure drop and the weight
15 rising excessively.

According to a further advantageous configuration of the invention, the tubes are formed as flat tubes, preferably as extruded multichamber tubes, and the fins
20 are formed as corrugated fins, which together result in a brazed, pressure-resistant heat exchanger block with a high power.

In a further advantageous configuration of the invention, medium flows through all the tubes belonging to a row in parallel, and preferably medium flows through these rows of tubes in succession, in which case from tube row to tube row a so-called diversion over the depth takes place. The individual rows of
25 tubes therefore alternately have medium flowing through them from the top downward and from the bottom upward, resulting in a long path for the flow medium in the tubes and effective cooling.

35 In an advantageous configuration of the invention, the individual rows of tubes have tube segments or tube groups through which medium can flow in succession - the flow medium is diverted "over the width" of a row

of tubes, resulting in the advantage of a longer flow path and more extensive cooling of the flow medium.

In an advantageous refinement of the invention, just
5 some or all of the rows of tubes can be divided into
tube segments, so as to lengthen the flow path still
further. The number of tubes in the tube segments
corresponds to approximately half the number of tubes
of a row of tubes, but may also deviate from this
10 number, resulting in different tube segments.
Therefore, for example in the case of horizontally
arranged tubes, the flow velocity can be varied in the
lower or upper region of the block, and therefore so
too can the heat transfer.

15 In an advantageous configuration of the invention, each
row of tubes has its own corrugated fins, i.e. the
corrugated fins of adjacent rows of tubes are thermally
decoupled or thermally isolated, resulting in maximum
20 cooling of the flow medium.

However, in a further configuration of the invention,
it may also be advantageous to provide one common, i.e.
continuous corrugated fin for adjacent rows of tubes,
25 for example two rows of tubes. This in particular has
manufacturing technology benefits.

In a further advantageous configuration of the
invention, one common, continuous corrugated fin is
30 provided for all the rows of tubes, i.e. thermal
coupling is implemented between the individual rows of
tubes, resulting in a different temperature profile for
the flow medium.

35 In an advantageous configuration of the invention, the
tubes of adjacent rows of tubes are arranged aligned
with one another, which is a precondition for example

for continuous corrugated fins. This results in a lower pressure drop on the air side.

5 In a further advantageous configuration of the invention, however, the tubes may also be arranged offset with respect to one another, which although leading to a higher pressure drop on the air side does achieve a better heat exchanger power.

10 In a further advantageous configuration of the invention, the end face of the heat exchanger is square or at least approaches a square in terms of its height and width dimensions. An advantageous ratio of width to height is in the range from 0.8 to 1.2. This has the
15 advantage that a fan behind or in front of the end face is sufficient to deliver the cooling air, since it sufficiently covers the end face.

In a further advantageous configuration of the
20 invention, the end face has a surface area in the range from 4 to 16 dm², resulting in a smaller end face compared to conventional heat exchangers combined, at the same time, with a greater depth, i.e. the heat exchanger has a compact shape approaching a cube and
25 can therefore be arranged at any desired locations in the engine compartment. On the other hand, the power of the coolant cooler is no longer adversely affected by an upstream condenser or gas cooler.

30 In a further advantageous configuration of the invention, the abovementioned heat exchanger having the large number of refinements is used as a gas cooler in a supercritical refrigeration cycle of a motor vehicle air-conditioning system operated with CO₂. This
35 achieves all the advantages referred to above.

Exemplary embodiments of the invention are illustrated in the drawings and described in more detail in the text which follows. In the drawings:

- 5 Fig. 1a, 1b, 1c diagrammatically depict a heat exchanger according to the invention with four, five and six rows,
- Fig. 2a, 2b show the heat exchanger according to the invention having four rows, with the
- 10 last two or three rows divided into tube segments,
- Fig. 3a, 3b show a heat exchanger according to the invention having four rows, with all the rows divided into tube segments of an
- 15 identical or different arrangement,
- Fig. 4 shows a heat exchanger according to the invention with flat tubes and thermally decoupled corrugated fins,
- Fig. 5 shows a heat exchanger according to the invention with four rows of tubes, with
- 20 in each case two adjacent rows of tubes having one common corrugated fin,
- Fig. 6 shows a four-row heat exchanger according to the invention with continuous corrugated fin,
- 25 Fig. 7 shows a four-row heat exchanger according to the invention with tubes arranged offset,
- Fig. 8 shows a diagram plotting the power of the heat exchanger as a function of the
- 30 number of rows of tubes, with each row of tubes having a segment,
- Fig. 9 shows a diagram corresponding to that shown in Fig. 8, but with in each case
- 35 only two segments per row of tubes.

Fig. 1a, 1b and 1c diagrammatically depict first exemplary embodiments of a heat exchanger according to

the invention, which is designed and can be used as a gas cooler for a supercritical refrigeration cycle. In particular, this gas cooler can be used for a motor vehicle air-conditioning system operated with the refrigerant CO₂ (R744).

Fig. 1a shows a four-row tube system for a gas cooler 1, through which the refrigerant CO₂ flows and which is cooled by ambient air, the direction of flow of air being indicated by arrows L. The gas cooler 1 has four rows of tubes 1.1, 1.2, 1.3, 1.4 arranged in series in the direction of air flow L, which rows of tubes each have tubes running parallel to one another, indicated by arrows R. Each row of tubes 1.1 to 1.4 has the same number of tubes, through each of which medium flows in parallel. The individual rows of tubes are connected in series on the refrigerant side, i.e. they are connected to one another by refrigerant connections, represented by dotted arrows V. This connection V is referred to as a diversion of the refrigerant "over the depth", with the depth direction being opposite to the air direction L. The refrigerant first of all enters the leeward row 1.1, illustrated by a dotted arrow E, and then, after it has flowed through the individual rows, is three times diverted over the depth and after it has flowed through the windward row 1.4 leaves the gas cooler via the outlet A, as illustrated by a dotted arrow A. This flow model for air and refrigerant is known as cross-counter-current. The refrigerant CO₂ enters the gas cooler, i.e. the row of tubes 1.1, approximately at a pressure of 125 bar and a temperature of about 130 degrees Celsius. The temperature of the air which enters the gas cooler 1 through the row of tubes 1.4 is approximately 45 degrees. Since the CO₂ air-conditioning system is working in the supercritical range, the dissipation of heat takes place not through condensation at constant temperature - as is the case in the refrigeration cycle

using R134a - but rather with a falling temperature, i.e. a temperature gradient from 130 degrees Celsius to approximately 50 degrees Celsius. This temperature difference of 80 degrees Celsius is gradually reduced during flow through the individual rows of tubes 1.1 to 1.4. The numbers mentioned are examples, and in some cases the temperature difference is even greater, i.e. approx. 100° Celsius. The gas cooler 1 has what is known as a finned end face, which is the surface area of the row of tubes 1.4 acted on by air and having the dimensions $B \times H$ (width \times height). The definition applies to all the gas coolers according to the invention.

Fig. 1b shows another exemplary embodiment of the invention, namely a gas cooler 2 with five rows of tubes 2.1, 2.2, 2.3, 2.4, 2.5, which are arranged in series in the direction of air flow L and are also connected in series on the refrigerant side. Identical reference designations are used for parts which correspond to those shown in Fig. 1a: the refrigerant inlet is at E, its outlet is at A, the connection between the individual rows of tubes is effected by a connecting line V. Therefore, the gas cooler 2 differs from the gas cooler 1 only by the provision of an additional row of tubes, resulting in increased power of the gas cooler 2 compared to the gas cooler 1 (cf. also Fig. 8).

Fig. 1c shows a further exemplary embodiment of the invention, namely a gas cooler 3 with six rows of tubes 3.1 to 3.6. It is once again based on the same flow model as in Fig. 1a and 1b, i.e. cross-counter-current. After the refrigerant has entered at E, it is diverted five times V over the depth in the opposite direction to the direction of air flow L by the time it emerges at A. The structural design of the gas coolers 1, 2, 3 which are diagrammatically depicted here uses means

which are known from the prior art mentioned in the introduction, i.e. for example extruded multichamber tubes which are connected in parallel and the tube ends of which are held and sealed in header tubes. The connection V can be effected by tube bends or diversion chambers.

Fig. 2a and Fig. 2b show a further exemplary embodiment of the invention, in which a diversion over the width (or alternatively over the height), i.e. in the plane of the row of tubes, takes place within a row of tubes.

Fig. 2a diagrammatically depicts a gas cooler 4 with four rows of tubes 4.1, 4.2, 4.3, 4.4 having a refrigerant inlet E, a refrigerant outlet A and connections V between the individual rows of tubes 4.1 to 4.4, i.e. three diversions over the depth. The refrigerant flows through the first two rows of tubes 4.1, 4.2 in parallel, whereas in the subsequent rows of tubes 4.3, 4.4, the refrigerant is diverted over the width (which with respect to the horizontally illustrated tubes means a diversion over the height). The row of tubes 4.3 is divided into two tube segments (groups of tubes) 3a, 3b, each illustrated by three or two arrows in opposite directions, and the row of tubes 4.4 is divided into two tube segments 4a, 4b. The diversion from the tube segment 3a to the tube segment 3b is represented by an arrow U, and the diversion from the tube segment 4a to the tube segment 4b is illustrated by a further arrow U. Therefore, in both the rows of tubes 4.3, 4.4 the refrigerant covers twice the distance compared to the rows of tubes 4.1, 4.2, with the division of the rows of tubes 4.3, 4.4 into tube segments being selected differently, as can be seen from the illustration in the drawing.

Fig. 2b shows a refinement of the embodiment illustrated in Fig. 2 for a gas cooler 5, likewise with

four rows of tubes 5.1, 5.2, 5.3, 5.4. Once again, the same reference designations are used for identical parts or symbols. Medium flows through the first row of tubes 5.1 in parallel, whereas in the rows of tubes 5.2 to 5.4 which follow on the refrigerant side there is in each case a diversion U over the width; the rows of tubes 5.2 to 5.4 are divided symmetrically into identical tube segments 2a, 2b, 3a, 3b, 4a, 4b. The flow velocity of the refrigerant is lower in the lower region 2a, 3a, 4a than in the upper region 2a, 3b, 4b, on account of the different cross sections of flow. This division of rows of tubes into tube segments, combined with a diversion over the width, can effect a further increase in the power of the gas cooler (cf. Fig. 9).

Fig. 3a and Fig. 3b show further exemplary embodiments of the invention, with each row of tubes divided into tube segments and diversion over the width taking place in each row of tubes.

Fig. 3a shows a four-row gas cooler 6 with rows of tubes 6.1, 6.2, 6.3, 6.4, the individual rows of tubes each being divided into uneven tube segments 1a, 1b, 2a, 2b, 3a, 3b and 4a, 4b. The number of arrows symbolizes the number of tubes per tube segment, i.e. in this case there are tube segments having in each case two and three tubes, which constantly alternate with one another. Within a row of tubes, there is a diversion over the width from a three-tube segment to a two-tube segment, and from the latter there is a diversion over the depth to a three-tube segment, and so on, as shown in the drawing, which provides sufficient explanation. Therefore, the cross section of flow changes constantly from diversion to diversion, and therefore so does the flow velocity of the refrigerant, resulting in locally different heat transfer conditions within the gas cooler 6.

Fig. 3b shows a gas cooler 7 which represents a modification of the gas cooler 6, specifically with regard to the arrangement of the tube segments in each row of tubes. The only difference with respect to the gas cooler 6 is that the tube segments with two tubes are in each case located at the top and the tube segments having three tubes are in each case located at the bottom, resulting in a diversion V over the depth in each case from an upper two-tube segment 1b, 2b, 3b to a lower three-tube segment 2a, 3a, 4a. The power of the gas cooler can be further enhanced by dividing each row of tubes into two tube segments (cf. Fig. 9).

Fig. 4 shows a structural exemplary embodiment for a four-row gas cooler 8 having the rows of tubes 8.1, 8.2, 8.3, 8.4, through which air flows in the direction of flow of the arrows L. In accordance with the statements which have been made above, therefore, the refrigerant first of all flows through the row of tubes 8.1 and finally flows through the row of tubes 8.4. Each row of tubes 8.1 to 8.4 has flat tubes 9 which are arranged aligned with one another and which, on account of the system-based high pressures are preferably formed as extruded multichamber flat tubes, as is known from the prior art cited in the introduction. Corrugated fins 10, over which the air flows, are arranged between the flat tubes of each row 8.1 to 8.4. Continuous gaps s are in each case arranged between the individual rows of tubes, i.e. both the corrugated fins 10 and the flat tubes 9 are thermally decoupled, such that there is no direct heat-conducting connection between them. The distance h is referred to as the fin height, and the distance b is referred to as the tube width. The so-called transverse pitch t_R of the flat tubes 9 is $t_R = h+b$. The tube pitch t_R is identical for all four rows of tubes.

Fig. 5 shows a further structural exemplary embodiment of a four-row gas cooler 11 having the rows of tubes 11.1, 11.2, 11.3, 11.4. The direction of air flow is once again denoted by arrows L. Two rows, namely the first two rows of tubes 11.1, 11.2, and the last two rows of tubes 11.3 and 11.4, each have common, continuous corrugated fins 12, 13. The flat tubes 9 of the rows of tubes 11.1, 11.2 are therefore thermally coupled via the continuous corrugated fin 12, and there is also a thermal coupling in rows 11.3 and 11.4 effected by the continuous corrugated fin 13. By contrast, between the two double rows there is a gap s which runs transversely to the direction of air flow and effects thermal decoupling.

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Fig. 6 shows a further structural exemplary embodiment of the invention, namely a four-row gas cooler 14. The four rows of tubes 14.1 to 14.4 have common, continuous corrugated fins 15, i.e. all the rows of tubes are thermally coupled to one another. When the hot refrigerant enters the first row of tubes 14.1, therefore, heat can flow away in the direction of the temperature gradient via the corrugated fins 15, i.e. in the opposite direction to the direction of air flow L.

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Fig. 7 shows a further exemplary embodiment of the invention, namely a four-row gas cooler 16 with four rows of tubes 16.1, 16.2, 16.3, 16.4, the flat tubes 9 of which, as seen in the direction of air flow L, are arranged offset with respect to one another. Therefore, as in Fig. 4, the individual rows of tubes 16.1 to 16.4 have separate corrugated fins 10, i.e. the rows of tubes are thermally decoupled via gaps s. The offset arrangement results in an improved heat transfer for the narrow side, onto which the air flows, of the flat tubes 9.

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Fig. 8 shows a diagram plotting the power of the gas cooler according to the invention with different end faces against the number of rows of tubes, with medium flowing through a row of tubes in parallel, i.e. a row of tubes forming a single segment. The curves located above one another represent different end faces, the size of which is given in the legend in the top right next to the diagram. The gas cooler having the highest power also has the largest end face, namely $302 \times 300 \text{ mm}^2 = 9.06 \text{ dm}^2$. The bottom curve (stars) has the smallest end face of $202 \times 200 \text{ mm}^2 = 4.04 \text{ dm}^2$. The power of the gas cooler according to the invention in each case increases with the number of rows of tubes, with values having been determined and plotted for systems comprising from four to eight rows. A two-row system with an end face having an area of 20 dm^2 and a depth of 16 mm was selected as a basis for comparison for the gas cooler according to the invention. Two horizontal straight lines are plotted in the diagram for the power of this known gas cooler from the prior art, specifically a lower horizontal at 7.7 kW for idling and a higher horizontal at approximately 8.2 kW for a vehicle speed of 32 km/h in second gear. It can be seen from this comparison that with the gas cooler according to the invention, at least with the larger end faces, it is possible to achieve a higher power compared to the prior art.

Fig. 9 shows a similar diagram to Fig. 8, except that the values illustrated here are based on gas coolers having in each case two tube segments per row, i.e. a diversion over the width is realized in each row of tubes of a four-row, five-row, six-row, seven-row or eight-row system. The end faces for the individual curves can once again be found in the legend; these are the same end faces as in the diagram shown in Fig. 8. A comparison between the two diagrams clearly illustrates that with the same end face area but a diversion over

the width or two tube segments per row, it is possible to achieve a higher gas cooler power, which with larger end faces is well above that of the prior art, which is the same as in the diagram shown in Fig. 8. The
5 underlying end faces, moreover, are virtually square and are in a preferred area range from 4 to 9 dm² - in other words these are "handy" dimensions for the gas cooler according to the invention.